博士論文

Experimental Study on Behavior of E_1' Center in Quartz during Fault Slip

（断層すべりに伴う石英 E_1' 中心の挙動に関する実験的研究）

Kiriha TANAKA

令和４年

Abstract

Electron spin resonance (ESR) can detect the charge trapping center, which is a site (e.g., vacancy, impurity, and interatomic) trapping an electron or hole, in natural materials, such as minerals, archaeological artifacts, fossils, and natural resources. These have been useful in various studies, such as archaeological and geological datings (Ikeya, 1993), detection of seismic frictional heating (Fukuchi et al., 2005), characterizations of rock magnetic properties (Kumagai et al., 2018), and natural resource (Bulka et al., 1991; Wong and Yen, 2000; Sugahara et al., 2012). Among them, research in the field of dating has been specially advanced.

Fault dating using ESR is a method of estimating the age of the last fault activity (Ikeya et al., 1982). It assumes that charge trapping centers, whose number can be detected as the ESR intensity, accumulated due to exposure to natural radiation decrease to zero (known as zeroing) by a seismic fault slip at an earthquake (Fig. 1). However, whether the zeroing does not occur is unclear, hence, the zeroing condition and its mechanism are needed to be understood deeply. The E_1' center is one of the fundamental charge trapping centers in quartz ($\equiv SiO^{\bullet}$, where $-$ is a covalent bond and $\bullet$ is an unpaired electron, Jani et al., 1983). Previous studies have investigated the changes in the ESR intensity of the E_1' center by several processes of a seismic fault slip using rotary friction apparatuses (Hataya and Tanaka, 1993; Fukuchi, 2004; Kyoto Uni., 2017; Yang et al., 2019). They conducted ESR measurements for the samples before and after the friction and contradictory changes in the ESR intensity of the E_1' center have been reported. The first part of my dissertation reexamined the changes in the ESR intensity of the E_1' center due to a seismic fault slip using rotary friction apparatuses.

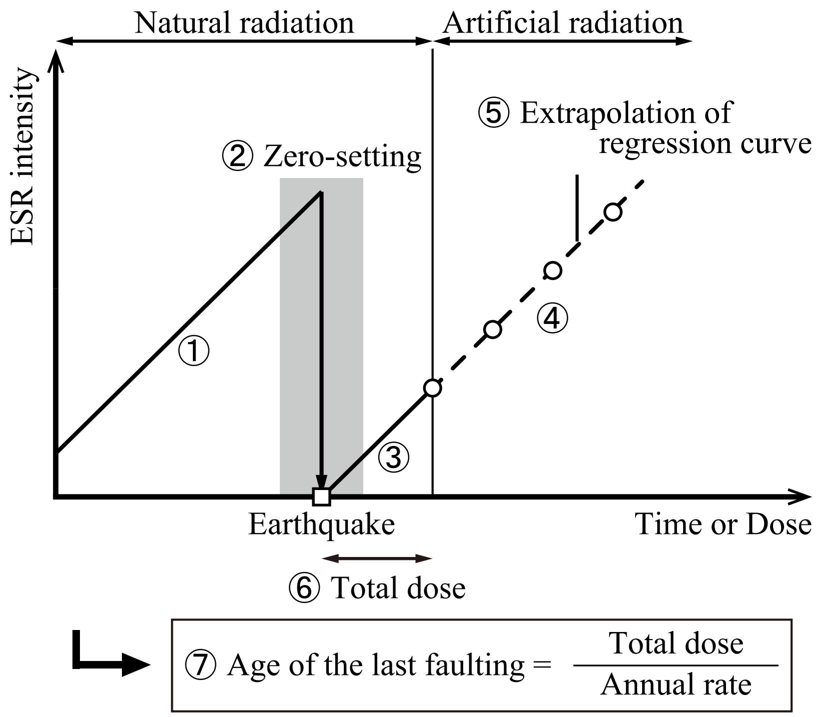

Fig. 1: The principle of fault dating using ESR (Tanaka et al., 2020).

The processes in a seismic fault slip include mechanical effects (grain fracturing and stress) and frictional heating. In Chapters 2 and 3, I found the relationships between mechanical effects of a fault slip and the absolute number of the E_1' center. The low-velocity friction (LVF) experiments simulating the mechanical effects were performed for natural quartz grains as the starting material of a simulated-fault gouge (Fig. 2). The numbers of the E_1' center in gouges before and after the LVF experiments were estimated by ESR measurements. To reveal the mechanisms of the changes in the number due to the mechanical effects of the LVF experiments, I acquired morphological features and ESR characteristics of the gouges. From the results of these experiments, I found that the number of the E_1' center increased due to grain fracturing which progressed with increasing displacement of a fault slip near the ground surface with a similar depth. Also, the number of the E_1' center increased with increasing normal stress due to grain fracturing up to certain stress and then decreased due to stress concentration between grains with increasing stress. It indicates that the number of the E_1' center can decrease due to stress concentration between grains accompanied by a fault slip with a normal stress beyond a certain value.

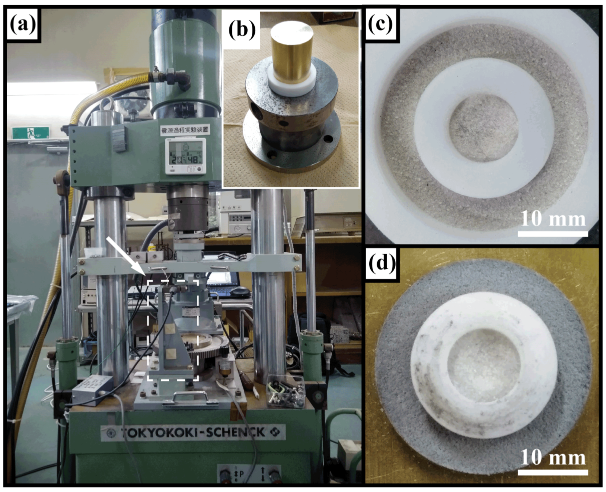

Fig. 2: The overall view of a low-velocity rotary shear apparatus and simulated-quartz gouge before and after shear tests (Tanaka et al., 2021). (a) A low-velocity rotary shear apparatus. A white arrow points a torque arm. (b) A part of an assembly to set in the apparatus. (c) Starting and (d) sheared quartz gouges on the surface of the brass forcing blocks. Note the color change of gouge after a shear test in (d).

In Chapter 4, the high-velocity friction (HVF) experiments simulating seismic fault slips were performed for quartz grains as the starting material of a simulated-fault gouge. The ESR intensity of the E_1' center of gouges before and after the HVF experiments were obtained by ESR measurements. To reveal the relationship between the ESR intensity of the E_1' center and grain fracturing, I observed the morphology of the gouges using a scanning electron microscope. Moreover, to discuss the effect of frictional heating on the ESR intensity of the E_1' center, the temperature changes within the gouges during the HVF experiments were acquired by thermocouple observation and finite element analysis. As a result, I discovered the relationship between seismic fault slips and the ESR intensity of the E_1' center.

The significant decrease of the E_1' center reported in previous studies could be attributed to the sensitivity reduction of ESR measurements by contaminants introduced during the friction experiments. In the present studies of Chapters 2–4, the ESR intensity of the E_1' center was obtained carefully, considering the effect of the contaminants on the ESR measurements. It is significant to remove the effects of contaminants on the ESR measurements to obtain more accurate results.

The voltage estimated from the charge trapping center in the SiO_2 film measured with a charging method was comparable with that measured during the friction of a quartz plate (Iwamatsu, 1986). Based on this finding, the generation mechanism of the seismo-electromagnetic phenomena (SEP) originating from the charge trapping center has been proposed (Takeuchi and Nagahama, 2002). This mechanism originates from the charge trapping centers formed in the surface amorphous layers of a fault due to fracturing as sources of the SEP. However, whether the charge trapping center can be the SEP source has not been investigated by direct measurement of the charge trapping center generated by fracturing. Moreover, previous studies have reported that discharge plasma due to frictional electrification could occur near the fault asperities during a fault slip before an earthquake (Muto et al., 2008). However, the details of electronic transition through the discharge plasma remain unclear. In the second part of my dissertation, I supported the generation mechanism of the SEP related to the charge trapping center and later revealed theoretically the electronic transition of the frictional discharge plasma.

In Chapter 5, I measured the number of the E_1' center in quartz grains produced by the low-velocity friction experiment simulating the fracturing of a fault slip before an earthquake using the ESR measurement. The surface charge density was estimated from the number of the E_1' center. This density was consistent with those estimated from the current or voltage changes on the frictional surface. From this discussion, I succeeded to support that the SEP could originate from the E_1' center.

In Chapter 6, the electronic transition through the fictional discharge plasma between minerals in nitrogen gas was theoretically discussed. I found that the frictional discharge plasma at fault asperities was not spatiotemporally thermally equilibrated. Furthermore, the discharge plasma was the spark and/or glow discharge caused by the de-excitation of neutral or ionized nitrogen molecules originating from the charge trapping center.

References

Bulka, G.R., Nizamutdinov, N.M., Mukhutdinova, N.G., Khasanova, N.M., Galeev, A.A. and Vinokurov, V.M., 1991. EPR probes in sedimentary rocks: the features of Mn^{2-} and free radicals distribution in the Permian formation in Tatarstan. Appl. Magn. Reson. 2 (1), 107–115. http://dx.doi.org/10.1007/BF03166271

Fukuchi, T., 2004. Fault activity dating by the ESR method —principles and practice— (in Japanese). Fukada Geological Institute. 63

Fukuchi, T., Mizoguchi, K. and Shimamoto, T., 2005. Ferrimagnetic resonance signal produced by frictional heating: a new indicator of paleoseismicity. J. Geophys. Res. 110 (B12), B12404

Hataya, R. and Tanaka, K., 1993. Studies on applicability of fault dating by ESR method (1) —experiments on zero-setting of ESR signals in quartz— (in Japanese with an English abstract). CRIEPI Res. Rep. U93019. Central Research Institute of Electric Power Industry. Abiko, Japan. 26p.

Ikeya, M., 1993. New Applications of Electron Spin Resonance: Dating, Dosimetry and Microscopy. World Scientific Publishing Co., Ltd., Singapore

Ikeya, M., Miki, T. and Tanaka, K., 1982. Dating of a fault by electron spin resonance on intrafault materials. Science 215 (4538), 1392–1393. http://dx.doi.org/10.1126/science.215.4538.1392

Iwamatsu, S., 1986. Distributions of hole and electron trapping centers in SiO_2 film on Si, and the relation with the electrostatic tribo electrification phenomena of quartz. Appl. Phys. Lett. 48 (22), 1542–1543. http://dx.doi.org/10.1063/1.96863

Jani, M.G., Bossoli, R.B. and Halliburton, L.E., 1983. Further characterization of the E_1' center in crystalline SiO_2. Phys. Rev. B 27 (4), 2285–2293. http://dx.doi.org/10.1103/PhysRevB.27.2285

Kumagai, Y., Nakamura, N., Sato, T., Oka, T. and Oda, H., 2018. Ferromagnetic resonance spectroscopy and rock magnetic characterization of fossil coral skeletons in ishigaki islands, japan. Geosciences 8 (11), 400. http://dx.doi.org/10.3390/geosciences8110400

Kyoto Uni., 2017. Deep borehole into Nojima fault. Fiscal Year FY 2015 Nuclear Regulation Agency Prevention Countermeasures Commission Achievement Report (in Japanese). Kyoto Uni.

Muto, J., Nagahama, H., Miura, T. and Arakawa, I., 2008. Frictional discharge plasma and seismo-electromagnetic phenomena. Phys. Earth Planet. Inter. 168 (1-2), 1–5. http://dx.doi.org/10.1016/j.pepi.2008.04.014

Sugahara, T., Kobayashi, Y., Tani, A., Inoue, T. and Ohgaki, K., 2012. Intermolecular hydrogen transfer between guest species in small and large cages of methane+propane mixed gas hydrates. J. Phys. Chem. A 116 (10), 2405–2408. http://dx.doi.org/10.1021/jp300814s

Takeuchi, A. and Nagahama, H., 2002. Interpretation of charging on fracture or frictional slip surface of rocks. Phys. Earth Planet. Inter. 130 (3-4), 285–291. http://dx.doi.org/10.1016/S0031-9201(02)00013-4

Tanaka, K., Muto, J., Nagahama, H. and Oka, T., 2020. A fault dating method using an electron spin resonance (in Japanese with an English abstract). Hoshasen Kagaku (110), 21–30

Tanaka, K., Muto, J., Yabe, Y., Oka, T. and Nagahama, H., 2021. Effect of fracture on ESR intensity using a low-velocity rotary shear apparatus. Geochronometria 48 (1), 205–214. http://dx.doi.org/10.2478/geochr-2020-0035

Wong, G.K. and Yen, T.F., 2000. An electron spin resonance probe method for the understanding of petroleum asphaltene macrostructure. J. Pet. Sci. Eng. 28 (1), 55–64. http://dx.doi.org/10.1016/S0920-4105(00)00067-X

Yang, L.H., Chen, J., Yao, L., Liu, C.R., Shimamoto, T. and Thompson, J.J.A., 2019. Resetting of OSL/TL/ESR signals by frictional heating in experimentally sheared quartz gouge at seismic slip rates. Quat. Geochronol. 49, 52–56. http://dx.doi.org/10.1016/j.quageo.2018.05.005